# LASER PROPULSION:

# FROM TSIOLKOVSKY TO UAH

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**The University of Alabama in Huntsville**

## Acknowledgements

**University of Alabama in Huntsville**

# LASER PROPULSION:
# FROM TSIOLKOVSKY TO UAH

## Outline

I.    Title

II.   Introduction to LP

III.  Timeline

IV.  UAH part

V.   Demo

# LASER PROPULSION:
# FROM TSIOLKOVSKY TO UAH

## Outline (Critical)

I.   **Title (awkward)**

II.  **Introduction to LP (questionable)**

III. **Timeline (irrelevant)**

IV.  **UAH part (unimpressive)**

V.   **Demo (goofy)**

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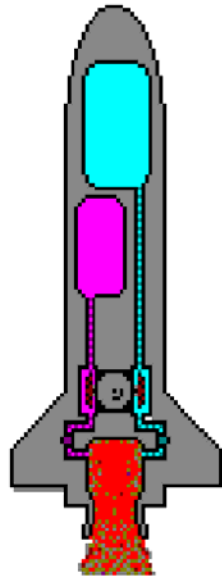
Vs.

- Laser Light Sails
- Laser Thermal
- Laser Electric

17.4 kW·h per 1 kg of a payload

3.2 kW·h per 1 kg of $H_2$

We need 5.4 kg of fuel for 1 kg of a payload, *at least\**.

Laser

Target

Plasma Plume
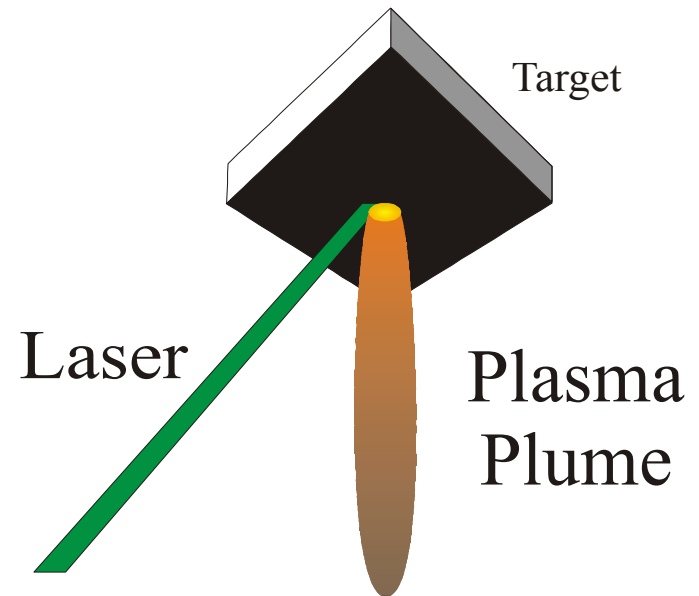
*Since oxygen and hydrogen are carried on-board, this number more than doubles.

**Laser Propulsion will bring revolutionary changes to all branches of space propulsion from satellite attitude control to space launching and even interstellar travel.**

# Laser Propulsion Timeline:

- Archimedes: Syracuse 214 B.C.

- Tsiolkovsky-Bernal-Sänger-Marx

- Maiman: Malibu 1960

- Kantrowitz: Avco-Everett 1972

- Myrabo: White Sands MR 1987

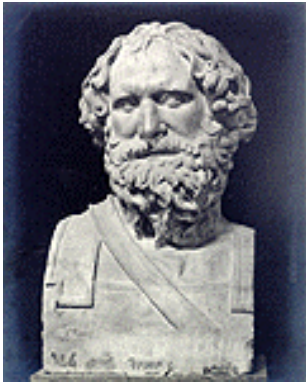- ISBEP: Huntsville 2002, Sendai 2003, Troy 2004

Time: 214 B.C., Place: Syracuse

# BOOK OF HISTORIES (CHILIADES)

## by John Tzetzes (circa XII century AD)
## BOOK II

When Marcellus withdrew them [his ships] a bow-shot, the old man [Archimedes] constructed a kind of hexagonal mirror, and at an interval proportionate to the size of the mirror he set similar small mirrors with four edges, moved by links and by a form of hinge, and made it the center of the sun's beams -- its noon-tide beam, whether in summer or in mid-winter. Afterwards, when the beams were reflected in the mirror, a fearful kindling of fire was raised in the ships, and at the distance of a bow-shot he Turned them into ashes. In this way did the old man prevail over Marcellus with his weapons.
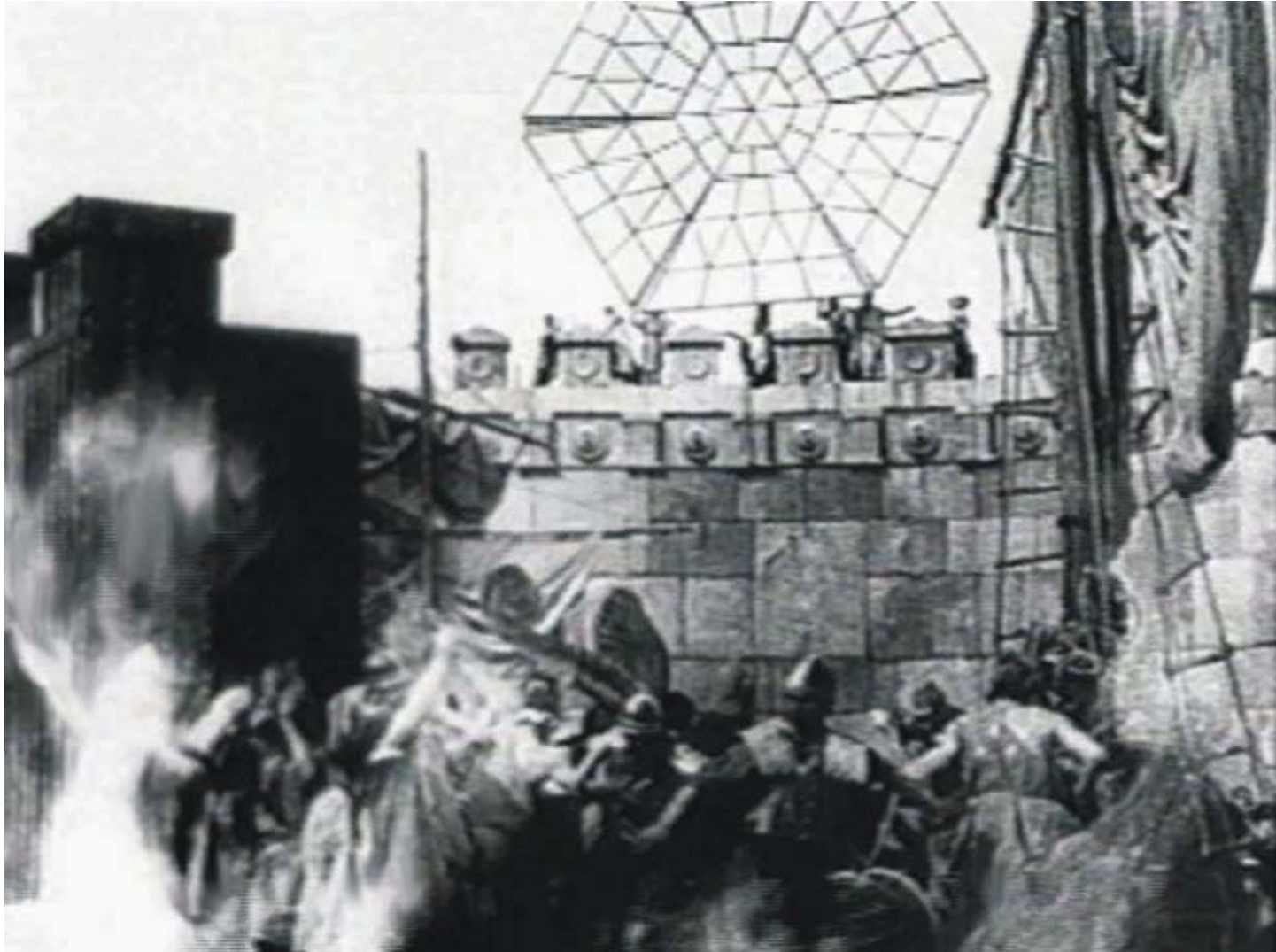
Gallery Uffizi (Florence, Italy).
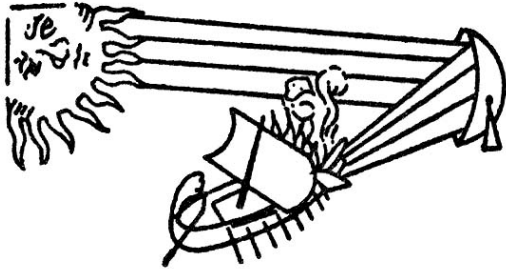Painted by Giulio Parigi (1571-1635) in 1599-1600.

# Italian silent movie "Cabiria", 1914

trattoria Archimede

Byzantine architect Anthemius of Tralles (d. 534 AD), the celebrated designer of St. Sophia Church in Constantinople, sculptor and mathematician, experimented with burning mirrors and actually wrote a brief treatise on the subject.

In 514 AD, Proclus destroyed with burning mirrors the fleet of Vitellius besieging Constantinople.  Was Anthemius a mastermind of this victory?  Perhaps, it was not just a mere coincidence that Proclus and Anthemius were contemporaries.

# History, cont.:
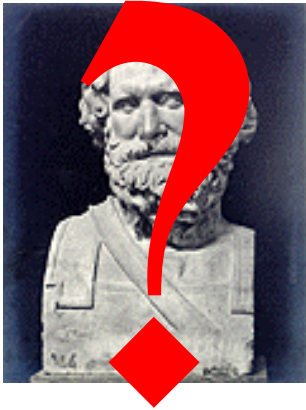
During the European Renaissance the skepticism about Archimedes mirrors was raised by Johannes Kepler (1571-1630) and René Descartes (1596-1650), who viewed the story as a mere myth.  Perhaps, in order to address such doubts, the experiments with burning mirrors were conducted at different times by A. Kircher (c. 1646), G.L.L. de Buffon (1747) and F. Peyrard (1808). Their studies proved that an old legend most likely is a true story.
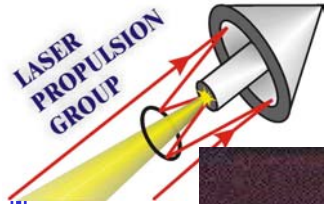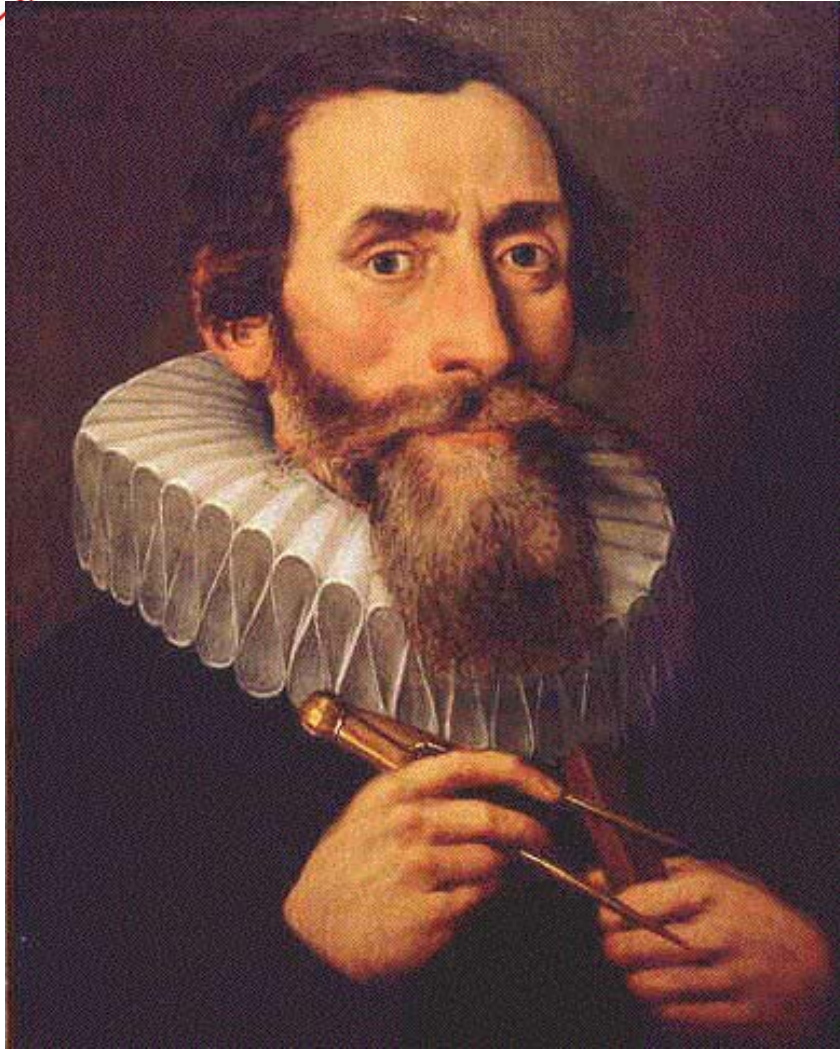
**Johannes Kepler**:
"Provide ships or sails adapted to the heavenly breezes, and there will be some who will brave even that void".
letter to Galileo, 1610
*Kepler was referring to his study of comet tails, which are always directed away from sun. In 1619 Kepler explained this phenomenon as an effect of sunlight pressure.*
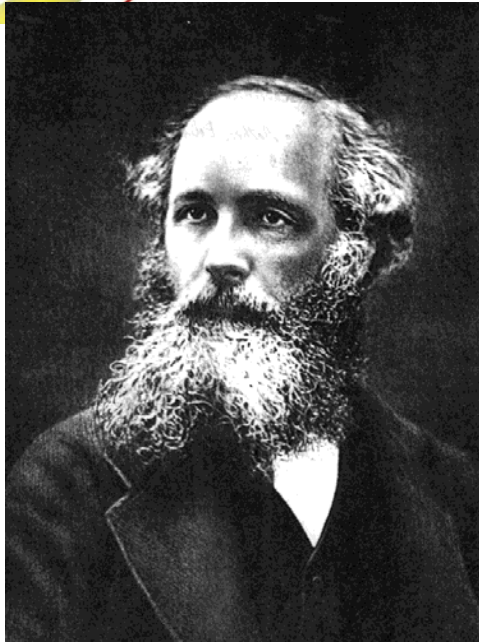
Johannes Kepler (1571-1630)

On the same account, **Rene Descartes** in 1638 suggested that light is a pressure wave, propagating in a special medium. This was a reinstatement of the concept of *aether* known since Aristotle.

René Descartes (1596-1650)

## History, cont.:

A scientific theory of light pressure was developed by **James Clerk Maxwell** in 1873. The first successful experimental proof of light pressure was presented in 1899 by Russian physicist Pyotr Nikolaevich Lebedev (1866-1912) and, independently in 1901, by American physicists Ernest Fox Nichols (1869-1924) and Gordon Ferrie Hull (1870-1924)

In a meantime, the idea of solar energy for propulsion was evolving along its own way. The first work on solar motor was resented in 1615 by Salomon de Caux, while first operational steam engines driven by solar energy were built by August Mouchot over period of 1864 – 1878.

•Light Sails: Using light momentum for space propulsion:

Kepler – Descartes – Maxwell - ?

someone had to put these ideas together

•Light Thermal: Using solar (light) energy for burning/heating +

•anything, but space propulsion:

Archimedes – Anthemius - Kirchner – de Buffon – Peyrard –

de Caux – Mouchot - ?

Konstantin Eduardovich Tsiolkovsky (1857–1935)

*"At last, there is a third, the most enticing method of obtaining speed. This is energy transfer to a missile from without, from the earth. The missile itself could not be supplied with material (i.e., weight, in the form of explosives or fuel) energy. It would be transmitted from the planet in the form of a parallel bundle of electromagnetic beams, with small wavelength."*

"Spacecraft", 1924.

*The Planet is a cradle of the mind,*
*but one can not forever live in a cradle.*

*Планета есть колыбель разума,*
*но нельзя вечно жить в колыбели.*

Konstantin Eduardovich
Tsiolkovsky
(1857–1935)

*The next difficulty is that to set in motion any large rocket the mass of gas required is of the same order as the weight of the rocket itself, so that it is difficult to imagine how the rocket could contain enough material to maintain its propulsion for any length of time. When the radio-transmission of energy is effected half the difficulty will be removed and the projection may very well ultimately be effected by means of positive rays at high potential.*

John Desmond Bernal
(1901-1971)

From *"The world, the flesh and the devil: an inquiry into the future of the three enemies of the rational soul"*, 1929.

*In 1953 Eugen Sänger developed a theory of a photon rocket, an essentially a nuclear rocket which converts its propellant according to Einstein's formula $E = mc^2$ into light energy. The light is collimated then by a parabolic mirror, assuming that the source is placed in its focus, light pressure propels the rocket.*

Eugen Sänger
(1905-1964)
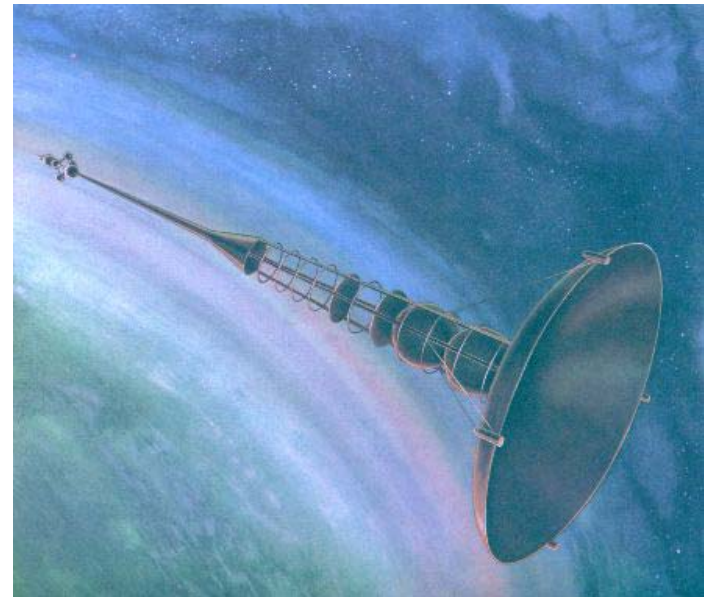
Sebastian von Hoerner (1917-2003)
"The general limits of space travel"
*Science*, Vol.13, July 1962.

Assuming LP = 6% von Hoerner estimated the distance to the nearest star system with possible intelligent life as approximately 5.6 parsec (18.6 light years). The distance to the technical civilization, *i.e.* the civilization technologically mature for interstellar space travel was estimated as 250 parsec (820 light years). The latter distance was supposed to challenge alien astronauts in case if they would like to visit the Earth.

N.R.A.O.

**Sebastian von Hoerner**

**(1917-2003)**

$$D = 5.6\, pc \left(\frac{T}{L}\right)^{1/3}$$

$T = 10$ billion years, oldest stars

$L = 100,000$ years, age of techno-civilization

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LSL

Photo by Mirjana Gearhart

von Hoerner

Then von Hoerner estimated one-way trip time assuming that the acceleration of the spaceship will be kept at 1 *g* and that half trip the ship will be accelerating, while another half it will be decelerating. The trip time appeared to be 12.3 years in the first case and 27.3 years in the second. Since the missions would require relativistic speeds, the trip times in the spaceship frame would correspond to 42 and 1550 Earth years respectively.

"*We may never visit our neighbors in space, but we should start listening and talking to them.*"

First, von Hoerner ruled out fission and fusion as energy sources for interstellar travel. Extreme outputs of energy per mass for fission ($1.1 \times 10^{18}$ ergs/g) and fusion ($8.3 \times 10^{18}$ ergs/g) lead to too heavy ships, too slow accelerations and, ultimately, too long trip times. Only matter-antimatter annihilation as an ultimate source of energy with energy density $9 \times 10^{20}$ ergs/g seemed providing enough power for interstellar travel.

Assuming that the mass of the spaceship is 10 tons and so is the mass of the power plant, and taking mass ratio $M = 10$, von Hoerner came to conclusion that in order to fulfill the trip time requirements given above:

*"We would need 40 million annihilation power plants of 15 magawatts each, plus 6 billion transmitting stations of 100 kilowatts each, altogether having no more mass than 10 tons, in order to approach the velocity of light to within 2 percent within 2.3 years of the crew's time".*

*"... The requirements, however, have turned out to be such extreme ones that I, personally, draw this conclusion: space travel, even in the most distant future, will be confined to our own planetary system, and a similar conclusion will hold for any other civilization, no matter how advanced it may be. The only means of communication between different civilizations thus seems to be electromagnetic signals".*
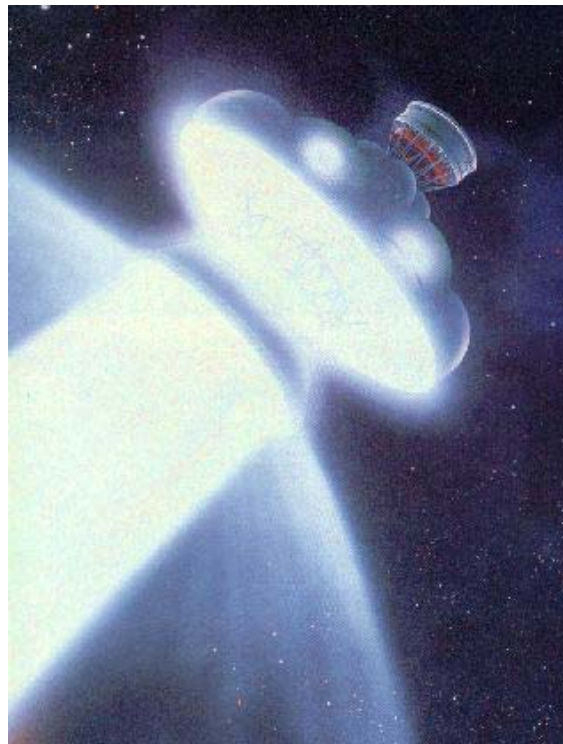
Sebastian von Hoerner

**George Marx** (1927-2002), professor of Roland Eötvös University (Budapest), profound lepton physicist and yet another SETI supporter, published a paper in *Nature*, 1966, titled "Interstellar vehicle propelled by terrestrial laser beam".

George Marx
(1927-2002)

**George Marx**:

*To achieve a relativistic velocity the vehicle would need to have a propellant energy, that greatly exceeds the most optimistic estimates of the technical possibilities in the foreseeable future. The reason for this is the very low mechanical efficiency of rocket propulsion in the relativistic domain. A rocket can be accelerated only by the reaction of its exhausted gases. The greater part of energy liberated from propellant is lost in the form of an unavoidable recoil motion of the small masses of the exhausted gas particles. This is a direct consequence of the conservation of energy and momentum. To prevent wastage of energy, the only possibility seems to be to transfer the recoil momentum to the Earth."*

Rocket Equation:

$$u_f = u_0 + v \ln\left(\frac{m_0}{m_f}\right)$$
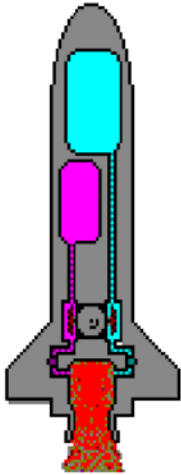
$v$ - speed of exhaust
$m_0$ - initial mass
$m_f$ - final mass
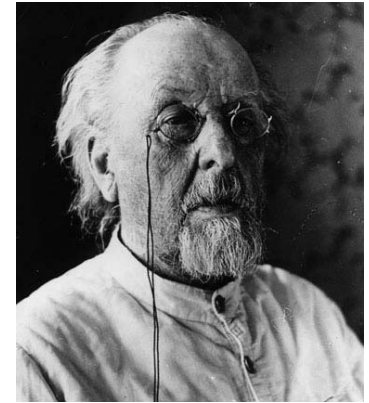$u_0$ - initial speed of a rocket
$u_f$ - final speed of a rocket



Konstantin Eduardovich
Tsiolkovsky
(1857–1935)

$$u_f = u_0 + v \ln(\mathrm{M})$$

For chemical rocket: $v$ = 4 km/s, corresponding to maximum temperatures possible in chemical reactions ~ $10^4$ K.

One order increase of $M$ from 10 to 100, leads to only doubling the speed of a rocket from 9.2 km/s to 18.4 km/s respectively.

In July 1969, Saturn V delivered Apollo 11 Command Service and Lunar Modules of total mass 43.8 tons to their historical destination. And yet, the three stages of this rocket had a mass about 2,900 tons. In other words, the Apollo 11 took 1.5% of Saturn V initial mass.

Konstantin Eduardovich
Tsiolkovsky
(1857–1935)

*"At last, there is a third, the most enticing method of obtaining speed. This is energy transfer to a missile from without, from the earth. The missile itself could not be supplied with material (i.e., weight, in the form of explosives or fuel) energy. It would be transmitted from the planet in the form of a parallel bundle of electromagnetic beams, with small wavelength."*
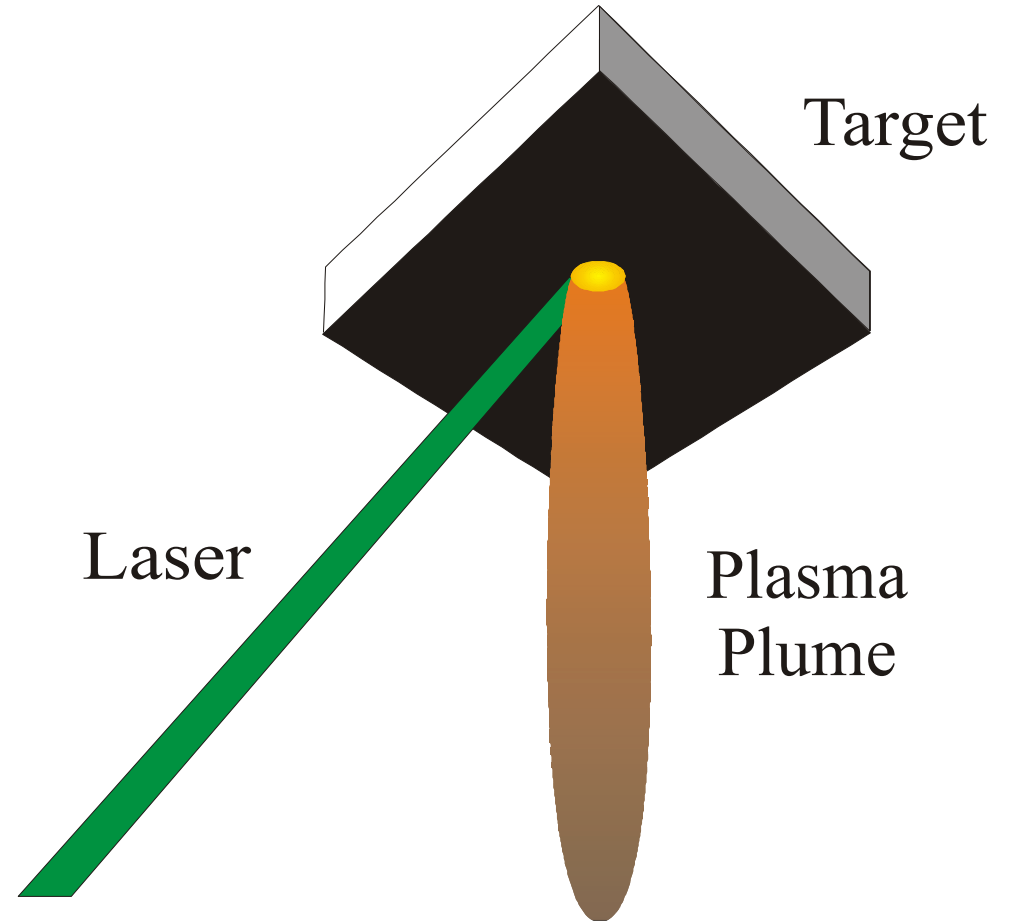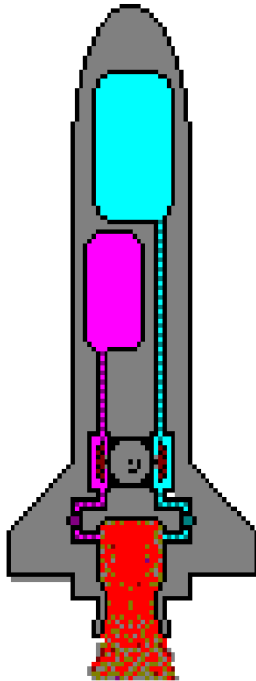
"Spacecraft", 1924.
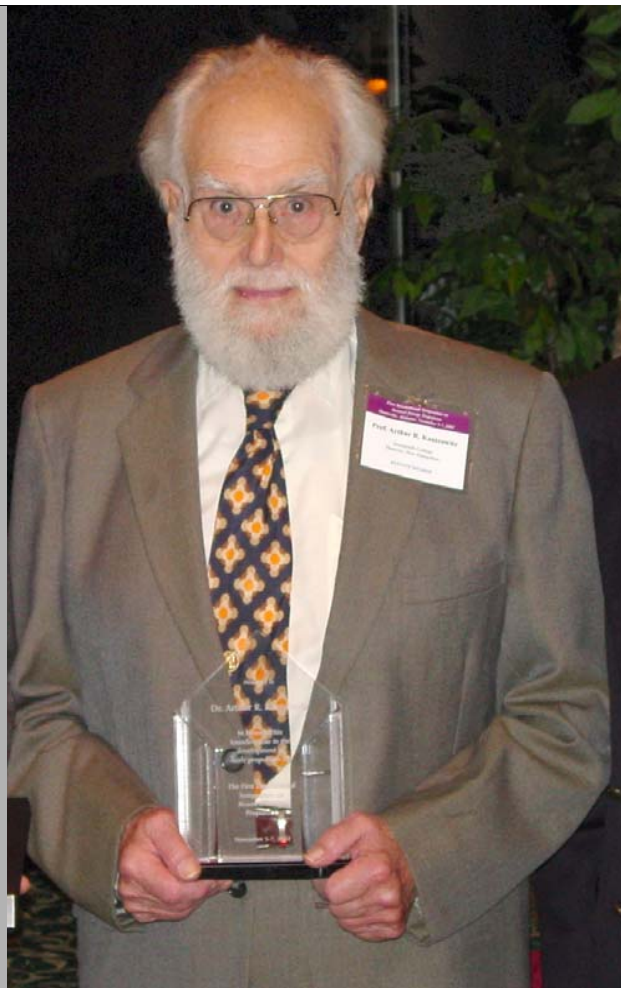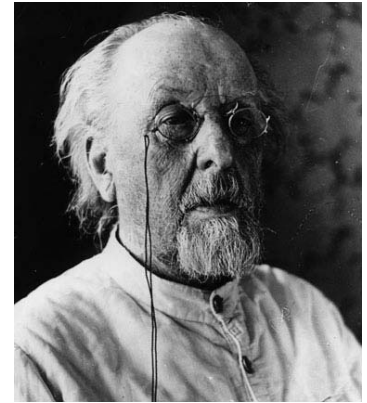
Dr. Arthur Kantrowitz,
ISBEP, 2002

Dr. Arthur Kantrowitz,
Dartmouth College, NH

Target

Laser

Plasma
Plume

$$u_f = u_0 + v \ln(\mathrm{M})$$

For laser-driven vehicle: $v = 200$ km/s,
(graphite ablation data)

For the same $u_f = 9.2$ km/s one will need $M = 0.05$
(not 10, as for a chemical rocket).

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$$u_f = u_0 + v \ln M - g_0 t_f$$

Now, let's set the mission parameters. We will assume that the task is to deliver 10-kg nanosatellite to LEO at 500 km altitude $h$ using laser propulsion. The velocity $u_f$ required for launching such satellite can be found from equation of motion:
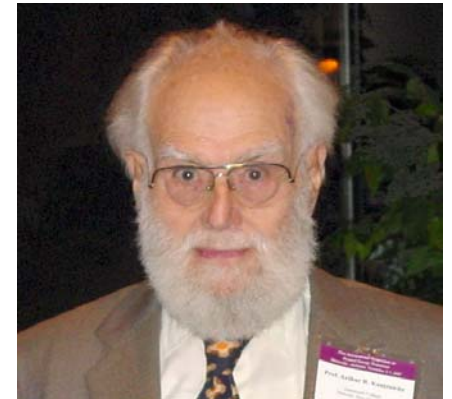
$$\frac{m_0 u_f^2}{R_\oplus + h} = \frac{G m_0 M_\oplus}{\left(R_\oplus + h\right)^2}$$

where $M_\oplus$ and $R_\oplus$ are Earth mass and radius respectively, and $G$ is universal gravitational constant.
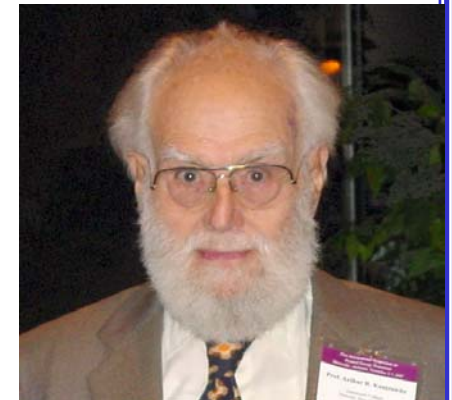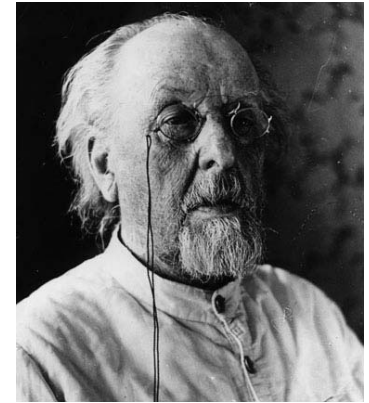
$$u_f = \sqrt{\frac{GM_\oplus}{R_\oplus + h}}$$

For $h = 500$ km $u_f \approx 7.9$ km/s.

Assuming that the satellite is accelerating to $u_f$ till it gets to $h = 500$ km, the required time will be 127 s and acceleration 6.3 $g_0$ . For a satellite of mass 10 kg the force (thrust) providing such acceleration is ~ 624 N.

Now we can estimate laser power required for such launch. To find out, we would need to use the so-called *coupling coefficient*, defined as a momentum, acquired by the vehicle per laser pulse energy. Traditionally, coupling coefficient denoted as $C_m$ is measured in dynes/Watt or N/MW. A realistic coupling coefficient for this estimation can be taken as 50 dynes/W. Then, the power of laser providing constant thrust of 624 N will be 1.2 MW.

Questions:
1. Is really $m_0 \approx m_f$?
2. How about laser beam divergence?
3. Is it true that LP propulsion will reduce payload price from $10,000 to $100 per kg?

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# Question 1: $m_0 \approx m_f$

As we have found, the time, required for given acceleration is 127 s. Using $v = 100$ km/s in Rocket Equation one will get $M = 1.1$. Therefore, an assumption $m_0 \approx m_f$ reasonably holds (propellant takes only 10% of the total mass).

## Question 2: *Beam Divergence*

Far-field half-angle beam divergence $\theta_{FF}$ for a laser can be defined as:

$$\theta_{FF} \cong \frac{\lambda}{\pi w_0}$$ , where $\lambda$ is laser wavelength and $w_0$ is laser beam waist.

Assuming that 1.2-MW laser will have a beam waist $w_0 = 0.5$ m and wavelength 532 nm, then $\theta_{FF} = 0.3$ μrad. Thus, such beam will be highly collimated, *i.e.* its divergence (2 cm) will be practically negligible over 30-km distance. Therefore, a large focusing mirror on the laser-propelled vehicle will not be required: the lightcraft will do well with a modest-size concentrator matching the beam diameter (1.0 m). Even at the set altitude of 500 km, the laser beam will be only 35 cm wider. In other words, the thrust will be still imparted to the vehicle!

Assuming modest 10% power efficiency of the laser, the system (when operating) would require 10 MW of electric power.
As we had found, the "burning" time for this launch is ~ 120 sec.
Let's take conservatively 3 min of laser operation per launch.
Then the transfer of the vehicle along the initial path *s* would require 0.5 MW·h of energy.  Taking electricity price of 10 ¢ for 1.0 kW·h, this would correspond to $50 per launch and, keeping in mind that we used example with 10-kg load, the energy price will fall down to $5 per kilogram!  Apparently, consumption of energy would not be setting the costs.

The real price will be carried by building and maintenance of 1-MW laser. According to modern sources, building of such system will cost from 1.0 to 3.0 billion dollars. However, unlike a disposable chemical rocket, such laser will provide practically permanent launching facility. In other words, it will be serving like a road to the space, or, using poetic term of Leik Myrabo, a "highway of light". 5,000 hours of operation of such system will deliver 1,000,000 kg of a payload mass to LEO. In current prices dictated by chemical propulsion, similar delivery would cost over 10 billion dollars, *i.e.* the laser-launch facility will pay-off the construction expenses over the first year of operation. On top of that price, maintenance of the system will be more likely on the level of 30 - 100 million dollars, constituting a financial revolution in space industry.

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5,000 hours of operation will deliver 1,000,000 kg of a payload mass to LEO for maximum 100 million dollars, correspond to:

Per 1 kg of a payload: $100 maintenance + $5 energy cost.

$105 per kg of a payload by laser propulsion *vs*. current $10,000 per kg by chemical rocket

Dr. Arthur Kantrowitz
ISBEP, 2002

Dr. Leik Myrabo,      Dr. Arthur Kantrowitz,
Rensselaer PI, NY    Dartmouth College, NH
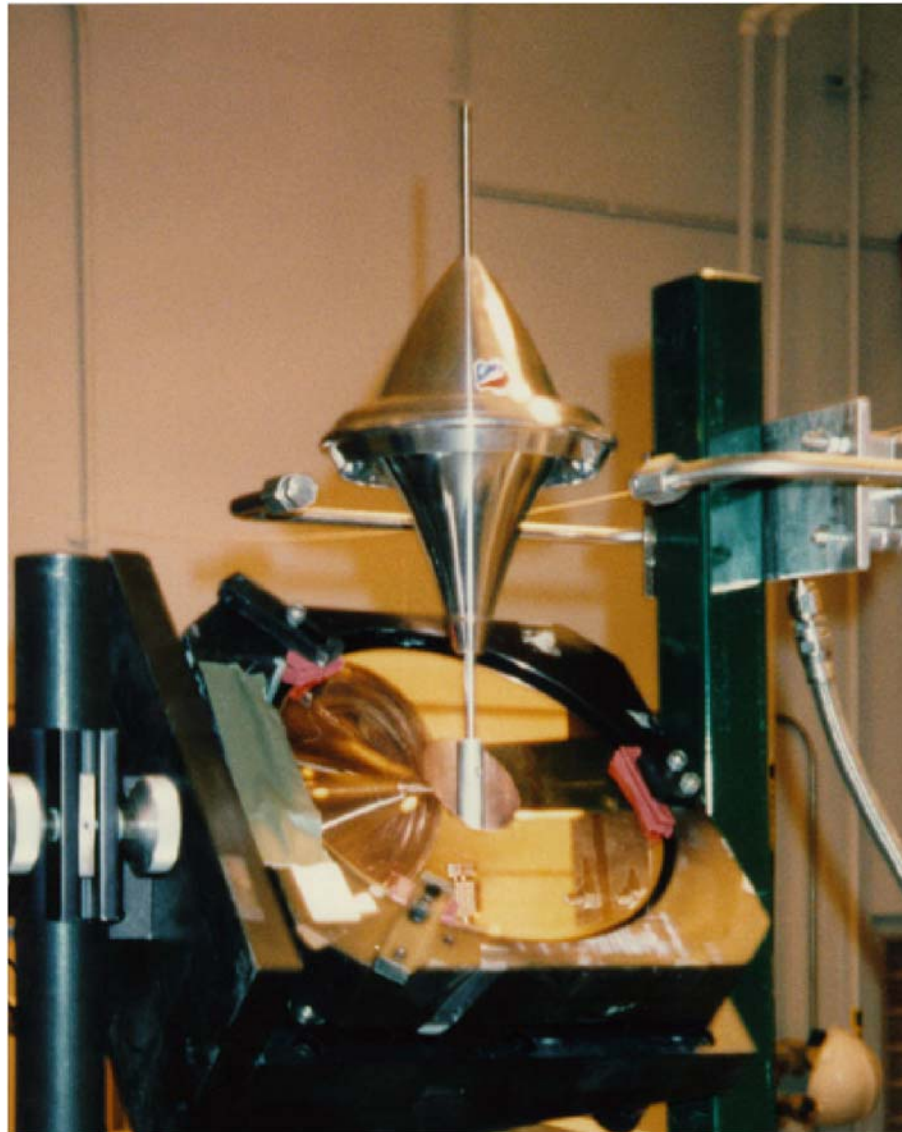
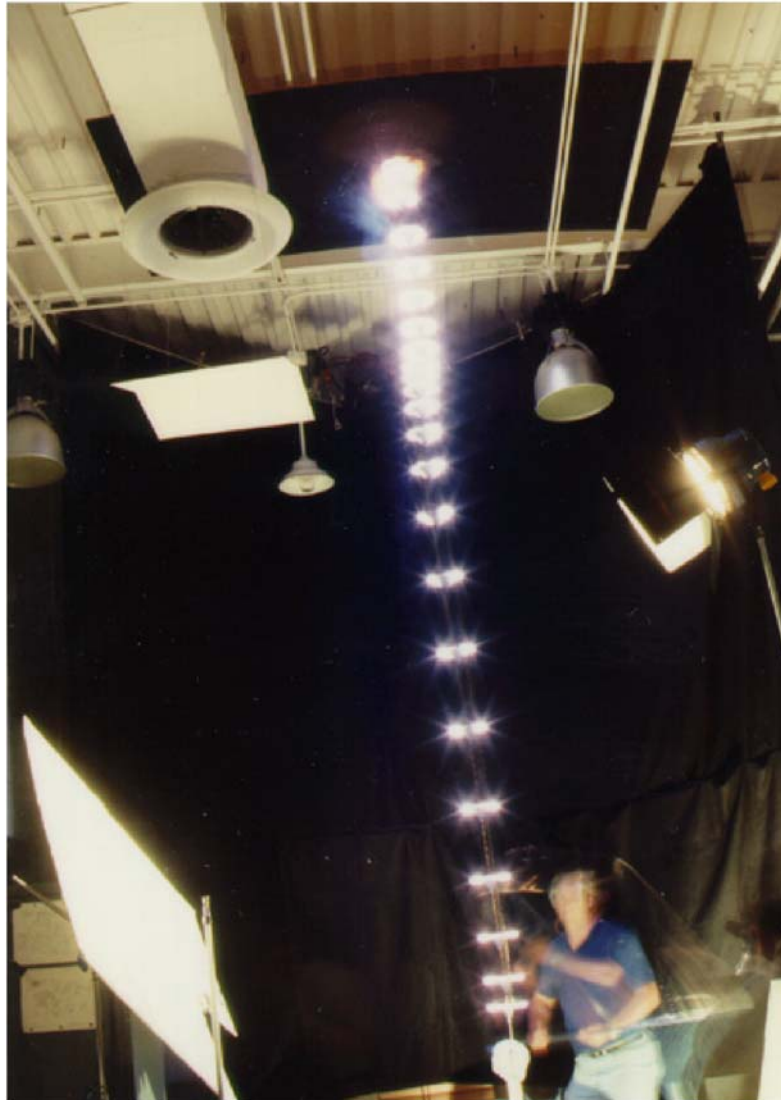# Myrabo Lightcraft



Courtesy of Dr. Leik Myrabo, RPI

# Myrabo Lightcraft Launch Pad



Courtesy of Dr. Leik Myrabo, RPI

# First Flights of Myrabo Lightcraft (1987, White Sands)



**Prof. Leik N. Myrabo**
Rensselaer Polytechnic
Institute, Troy, NY

Courtesy of Dr. Leik Myrabo, RPI

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Tregenna Myrabo, business manager of Lightcraft Technologies, Inc., holds Lightcraft Model 200. High Energy Laser Systems Test Facility at White Sands Missile Range, New Mexico, October 2, 2000.

# LASER PROPULSION
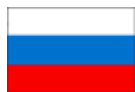
## ISBEP:

**Huntsville 2002**,
Participants: 113,
Countries/States: 8/15,
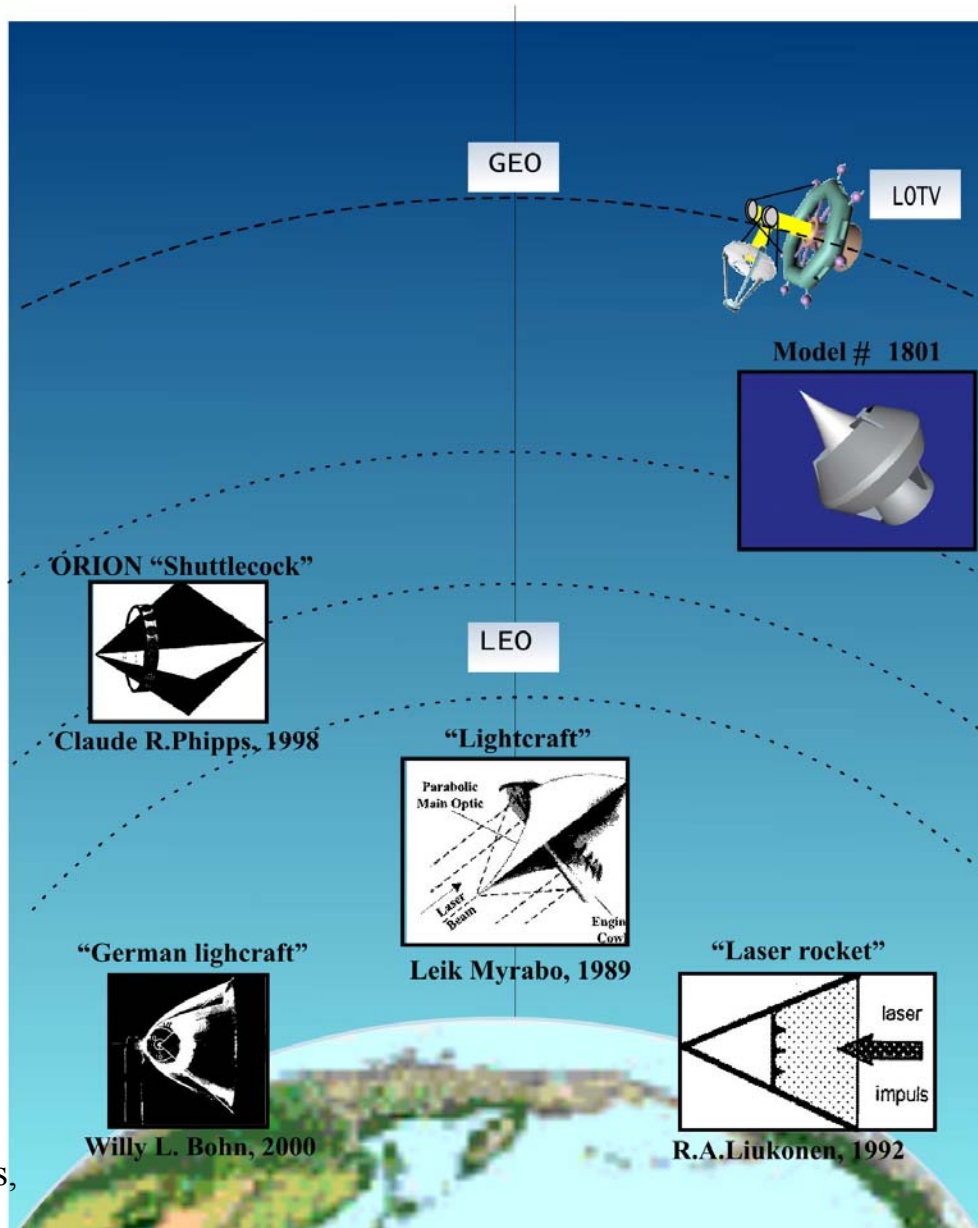Talks: 71
_____
**Sendai 2003**,
Participants: 98,
Countries: 8
Talks: 59
_____
**Troy 2004**

Courtesy of
Dr. Yuri Rezunkov,
Research Institute for
Complex Testing of
Optoelectronic Devices,
Sosnovy Bor, Russia

GEO

LOTV

Model # 1801

ORION "Shuttlecock"

Claude R.Phipps, 1998

LEO

"Lightcraft"

Parabolic
Main Optic

Laser
Beam

Engine
Cow

Leik Myrabo, 1989

"German lighcraft"

Willy L. Bohn, 2000

"Laser rocket"

laser

impuls

R.A.Liukonen, 1992

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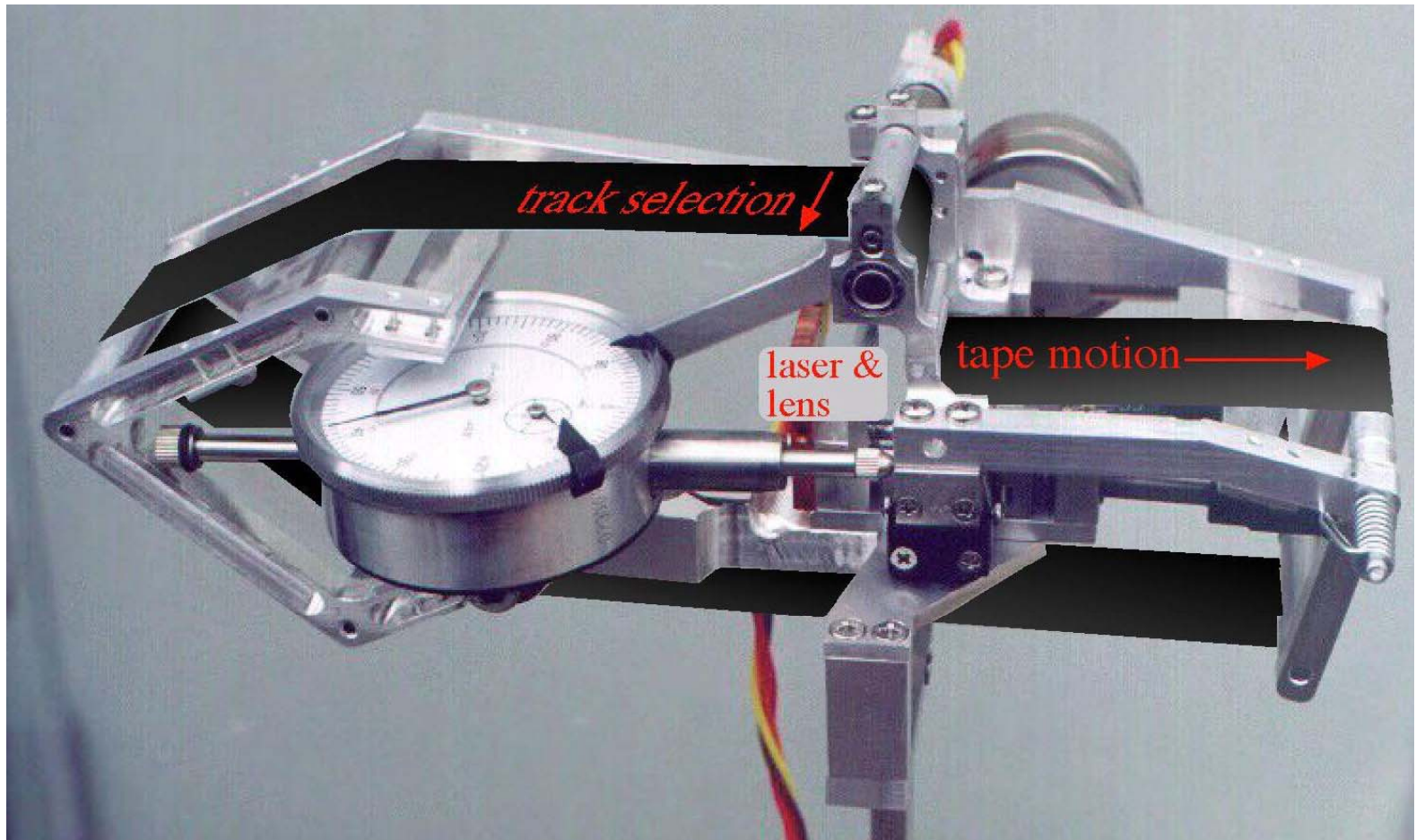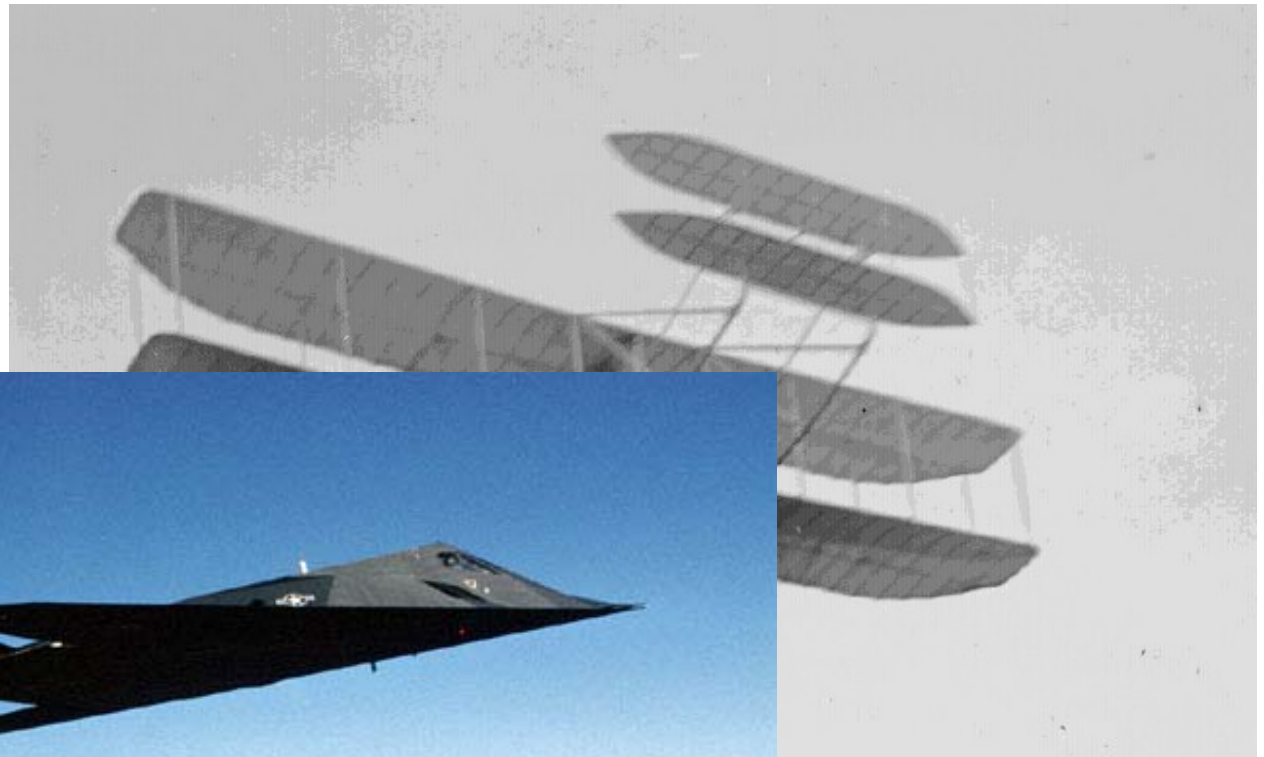
# Laser Microthruster
## (Claude Phipps, Photonic Associates, Santa Fe, NM)



Claude R. Phipps and James R. Luke,
Advantages of a ns-pulse micro-Laser Plasma Thruster
Presented at ISBEP 1, Huntsville, AL, Nov. 2002

1903 Wright's Flyer

F-117A Nighthawk

# **Future ?**

Demonstration
with an actual
Space Mission

Dr. Leik Myrabo,
Rensselaer PI, NY

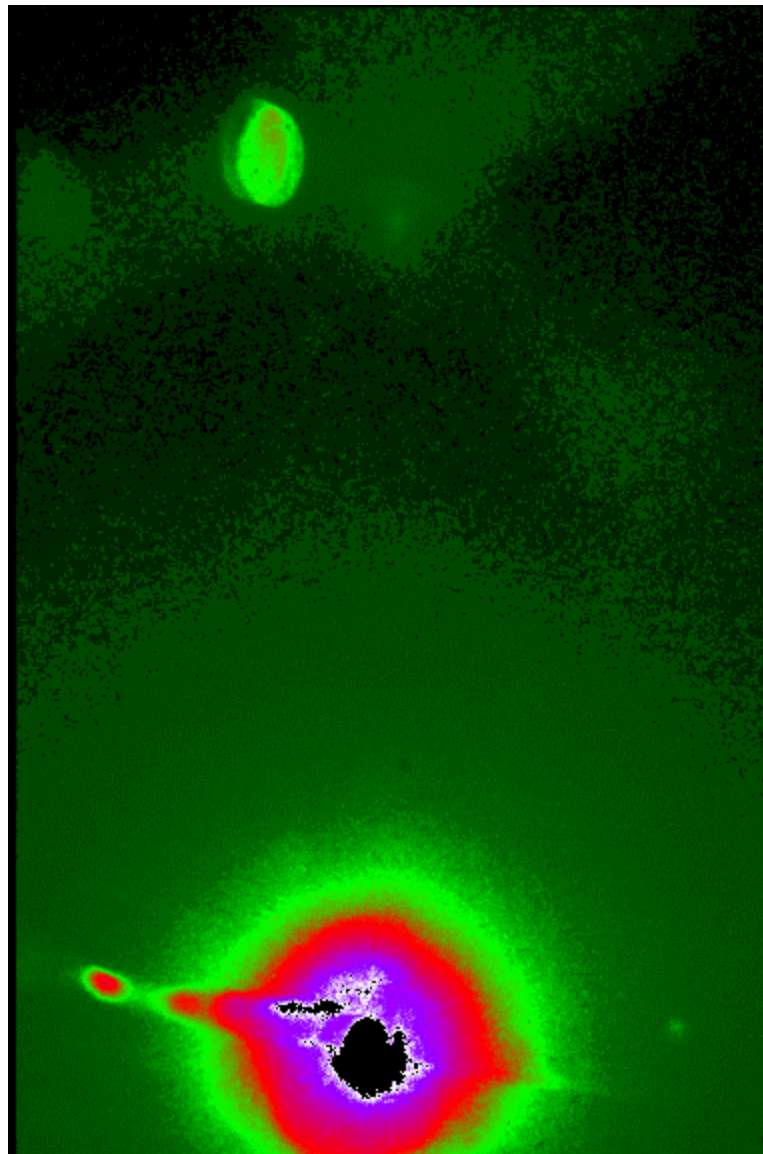Dr. Arthur Kantrowitz,
Dartmouth College, NH

One, who talks
right now

# ALP: ABLATION DOMINATED MOMENTUM TRANSFER

- **Short, high-energy laser pulses**

- **Material dependent ($I_{sp}$)**

- **Solid propellants**
    - x1000 lower breakdown thresholds
    - flat surface vs. volume, so:
    - tankage mass: ZERO
    - chamber mass: ZERO
    - mixed dynamics (fluid fuel + plasma) – NONE
    - directionality of exhaust
    - EM collimation of exhaust
    - $I_{sp}$ – $C_m$ control:
        - via propellant (rough)
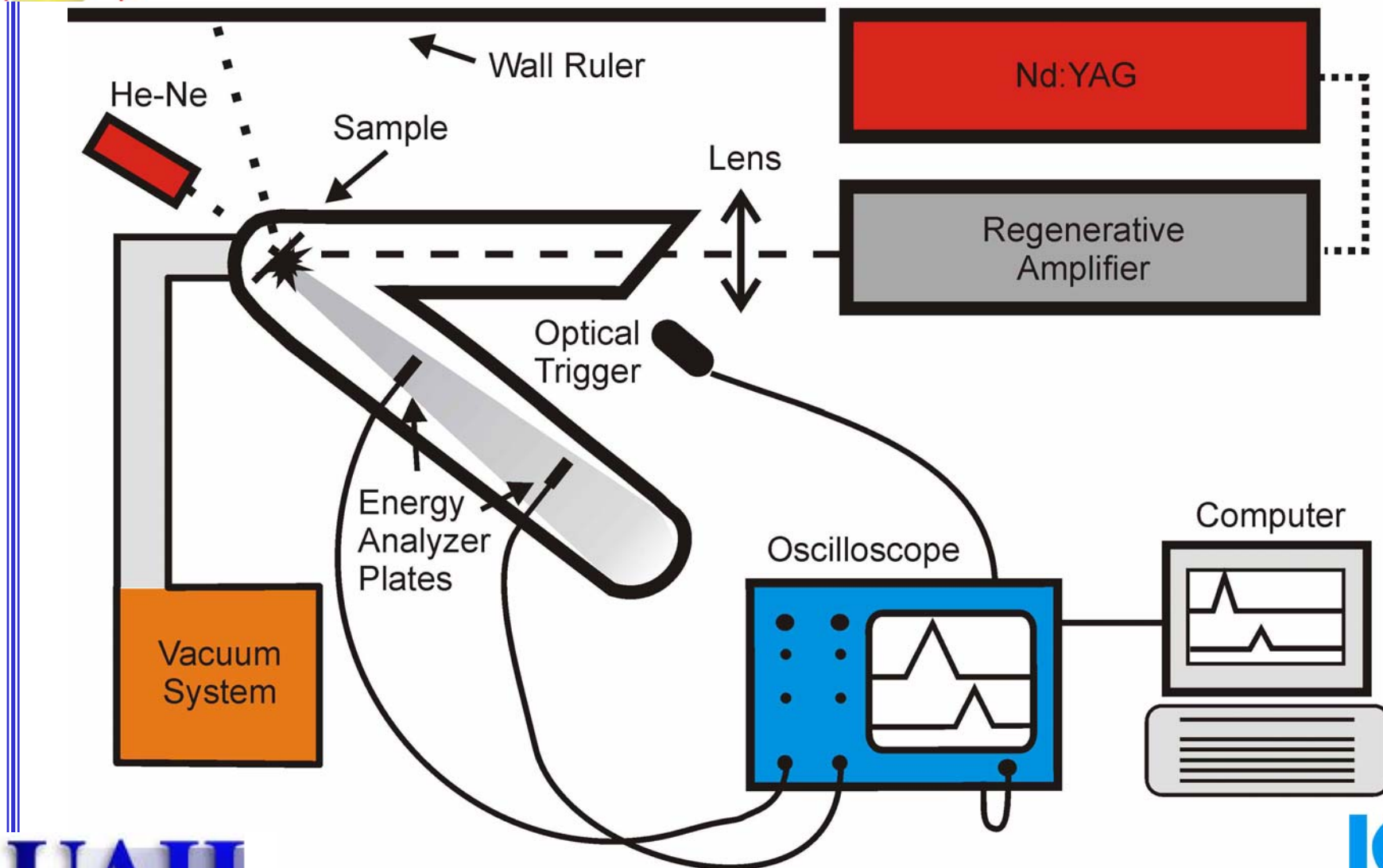        - via pulse separation (fine)

CW    ALP
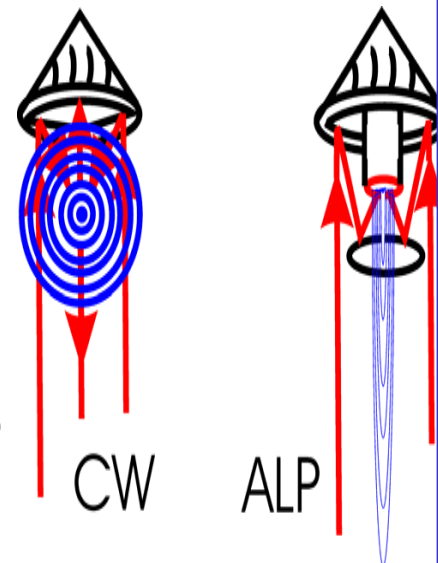
**Plasma Expansion From a Cu Target: 20 ns – 1.5 μs**
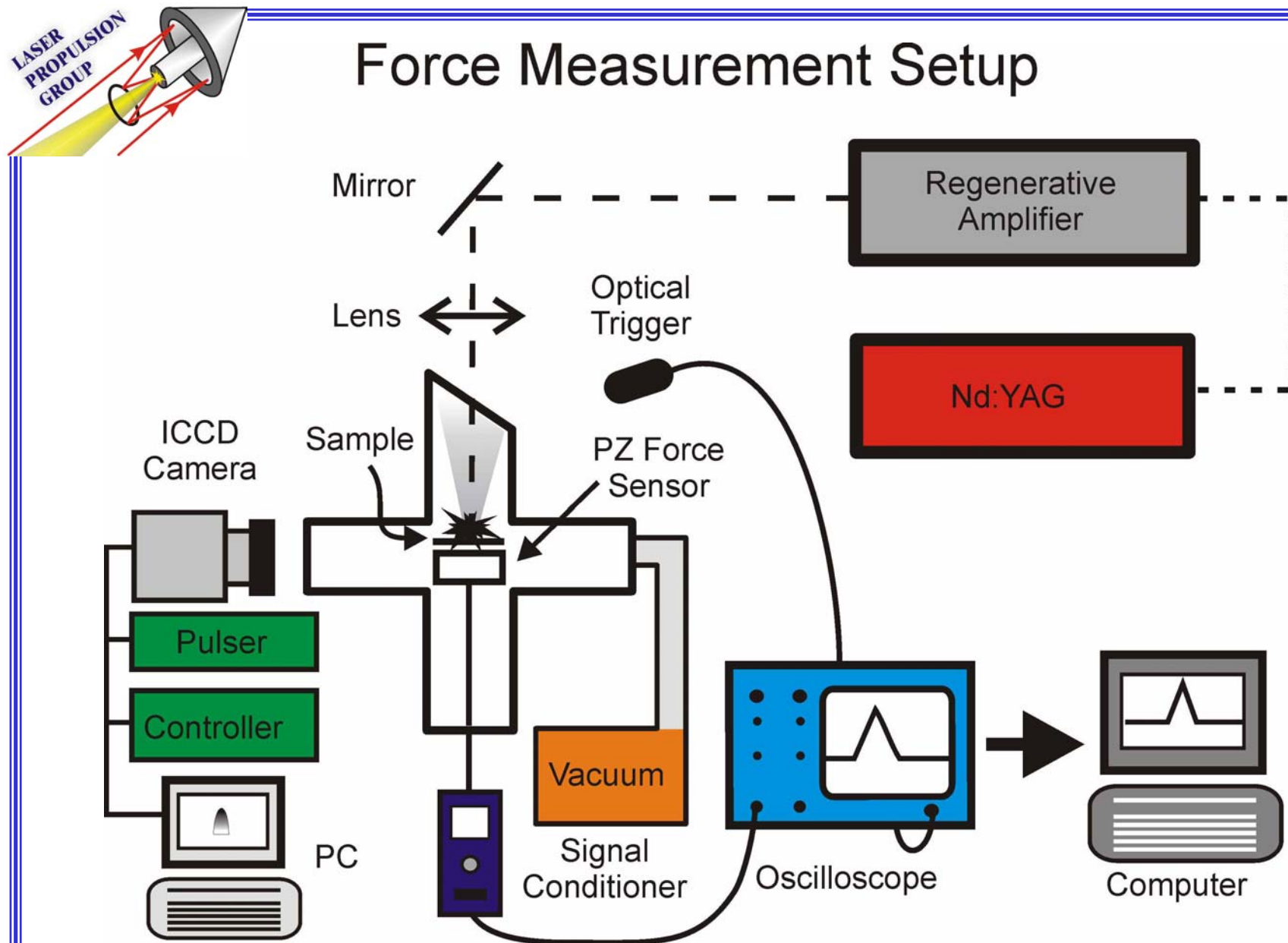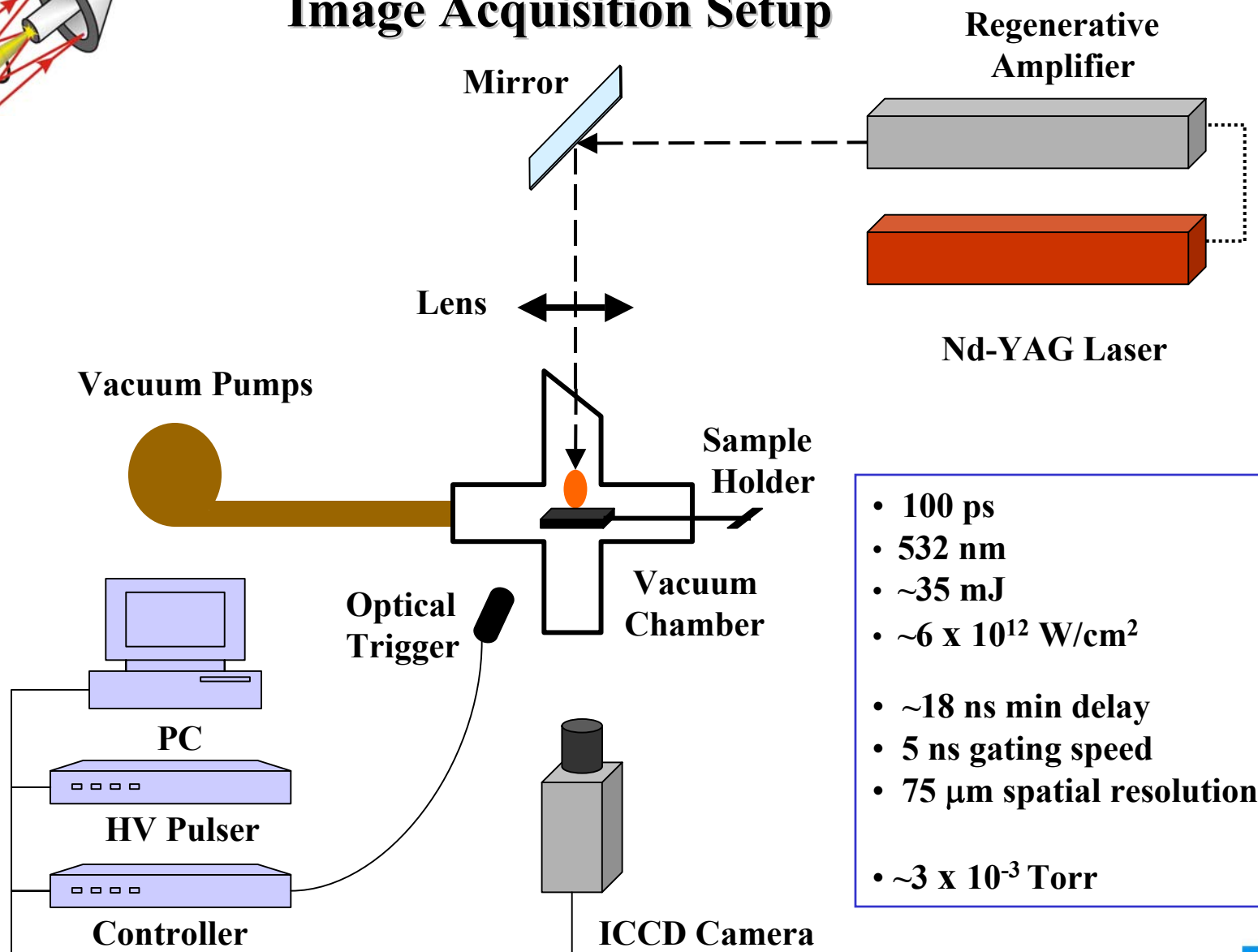
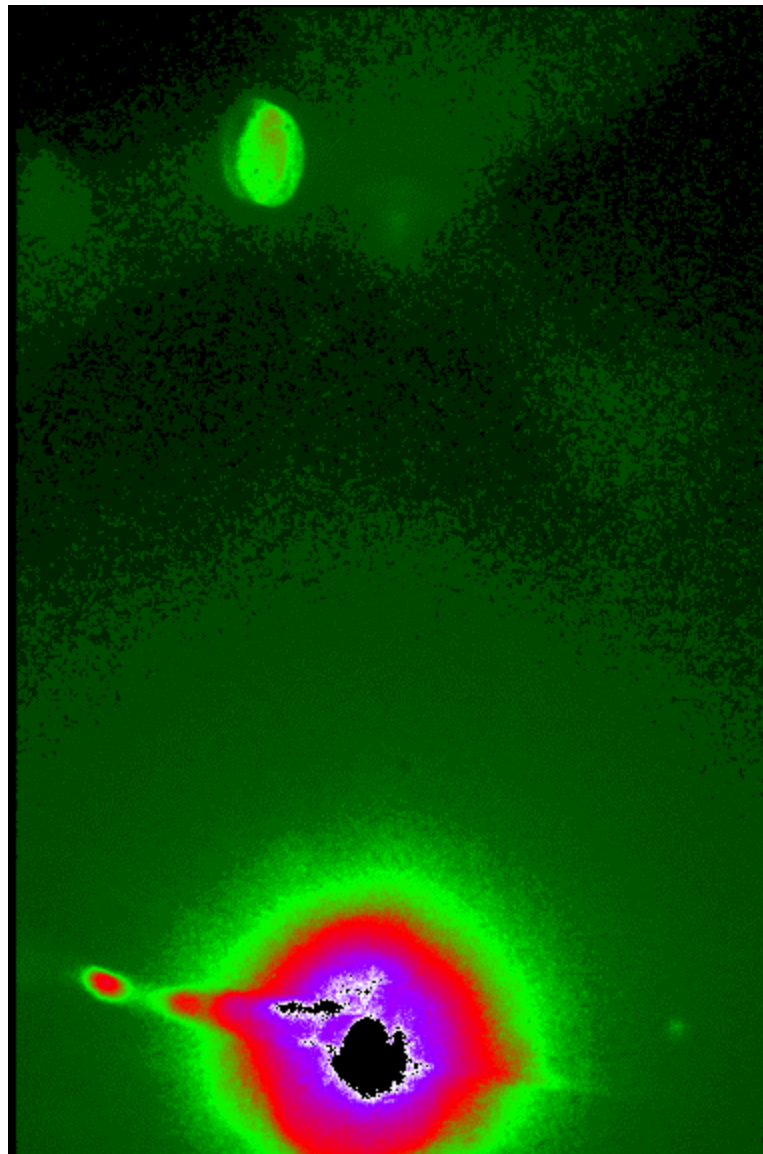# TOF Experimental Setup

# Force Measurement Setup



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# Image Acquisition Setup

**Regenerative Amplifier**

**Mirror**

**Nd-YAG Laser**

**Lens**

**Vacuum Pumps**

**Sample Holder**

**Vacuum Chamber**

**Optical Trigger**

**PC**

**HV Pulser**

**Controller**

**ICCD Camera**

- **100 ps**
- **532 nm**
- **~35 mJ**
- **~6 x 10$^{12}$ W/cm$^2$**

- **~18 ns min delay**
- **5 ns gating speed**
- **75 $\mu$m spatial resolution**

- **~3 x 10$^{-3}$ Torr**

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**Plasma Expansion From a Cu Target: 20 ns – 1.5 $\mu$s**
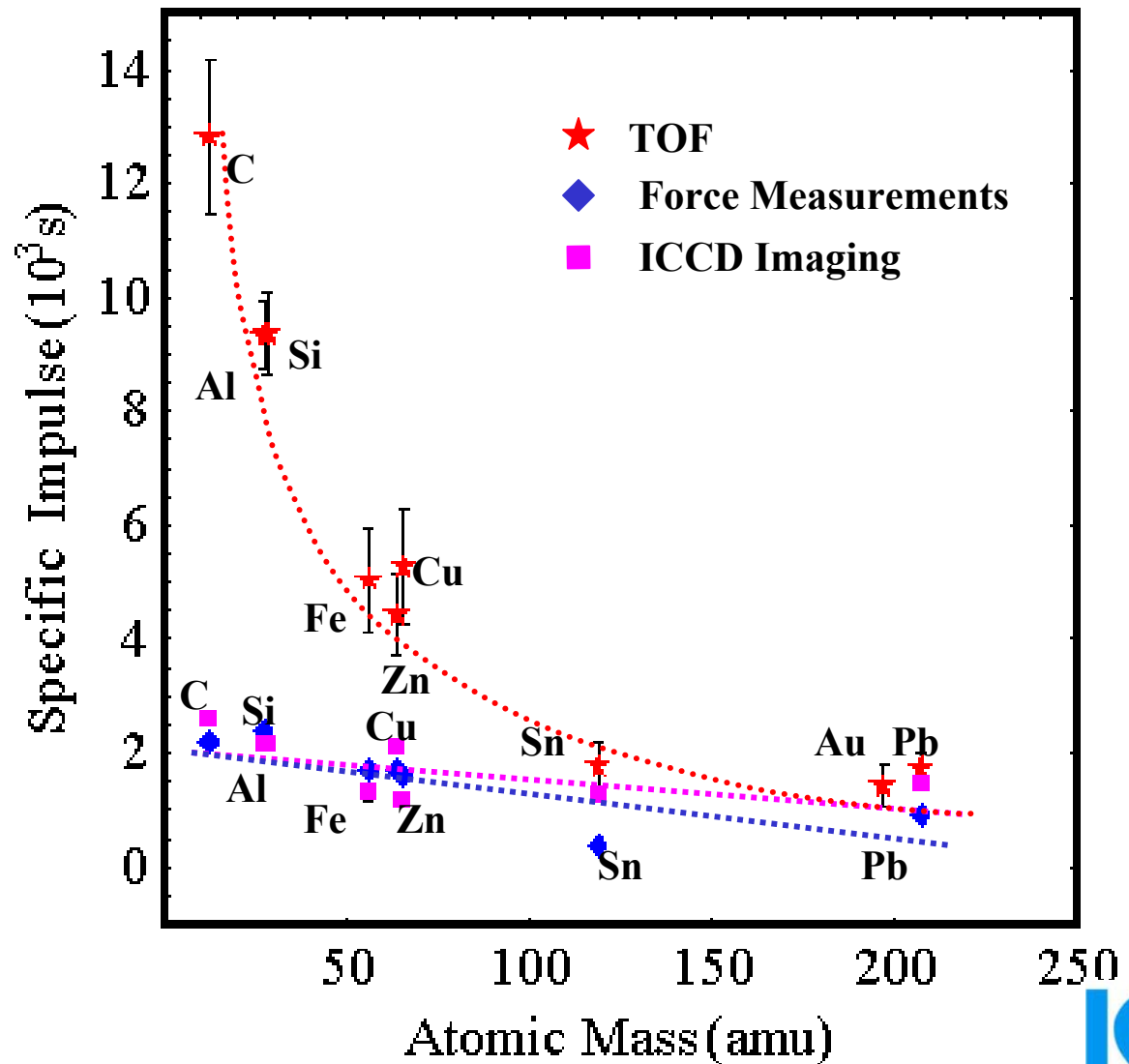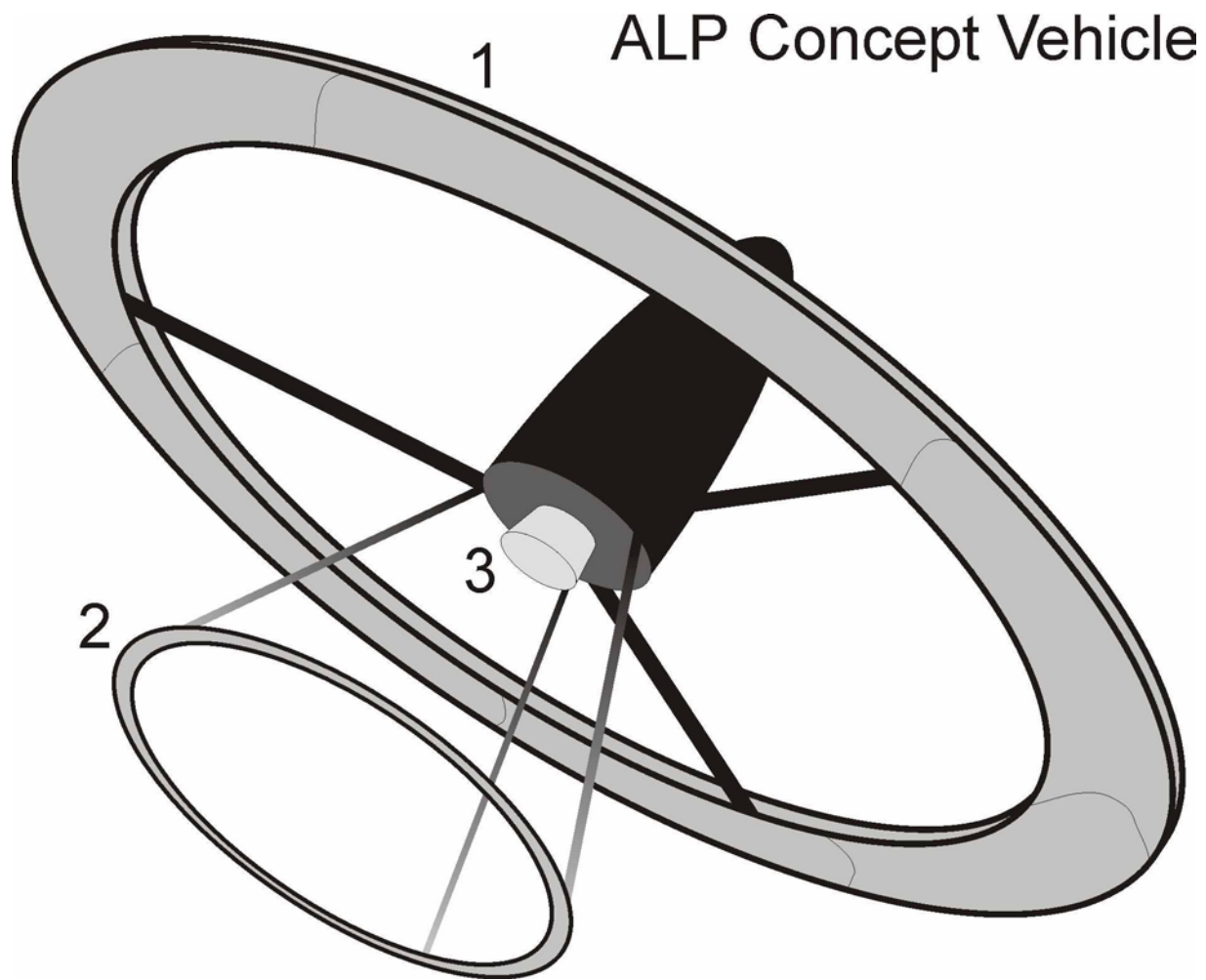
# Specific Impulse vs Atomic Mass

$$I_{SP} \equiv \frac{1}{W} \int_{t_0}^{t_f} F(t)dt$$

**vs.**

$$I_{SP} = \frac{\overline{P}}{W} = \frac{2}{3} \xi \frac{\overline{v}}{g_0}$$



Specific Impulse ($10^3$ s) vs Atomic Mass (amu)

Legend:
- ★ TOF
- ◆ Force Measurements
- ■ ICCD Imaging

Data labels: C, Al, Si, Fe, Cu, Zn, Sn, Au, Pb

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ALP Concept Vehicle
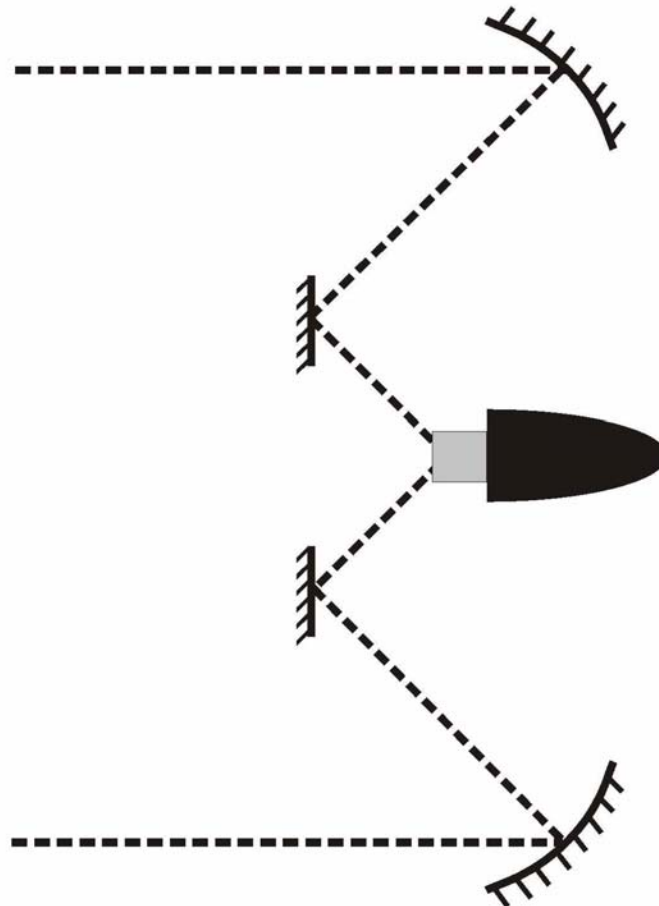
# Ray Tracing Diagram for ALP Concept Vehicle

Tregenna Myrabo, business manager of Lightcraft Technologies, Inc., holds Lightcraft Model 200. High Energy Laser Systems Test Facility at White Sands Missile Range, New Mexico, October 2, 2000.

$$\eta_0 \equiv \frac{E_V}{E_0} = \frac{W_m}{E_0}$$

$E_v$ - kinetic energy of the vehicle;
$W_m$ -work done by the vehicle over some time period $\delta t$ ;
$E_0$ – energy, beamed to the vehicle over the same period $\delta t$

Overall efficiency of Myrabo laser lightcraft: achieved on October 02, 2000. On this day MLL reached the record height of 233 ft (71 m) during 5.5 s-long flight. Neglecting the losses due to air resistance, we can estimate the mechanical work which the lightcraft did against the gravity as $mg_0h = 35$ J (the mass of the vehicle was ~ 50 g). The launches were conducted with $CO_2$ laser, emitting 450-J pulses with repetition rate ~ 27 Hz. For $\delta t = 5.5$ s this will correspond to $E_0 = 6.7$ kJ. The overall efficiency of the system is ~ 0.5 %.

# ALP Lightcraft
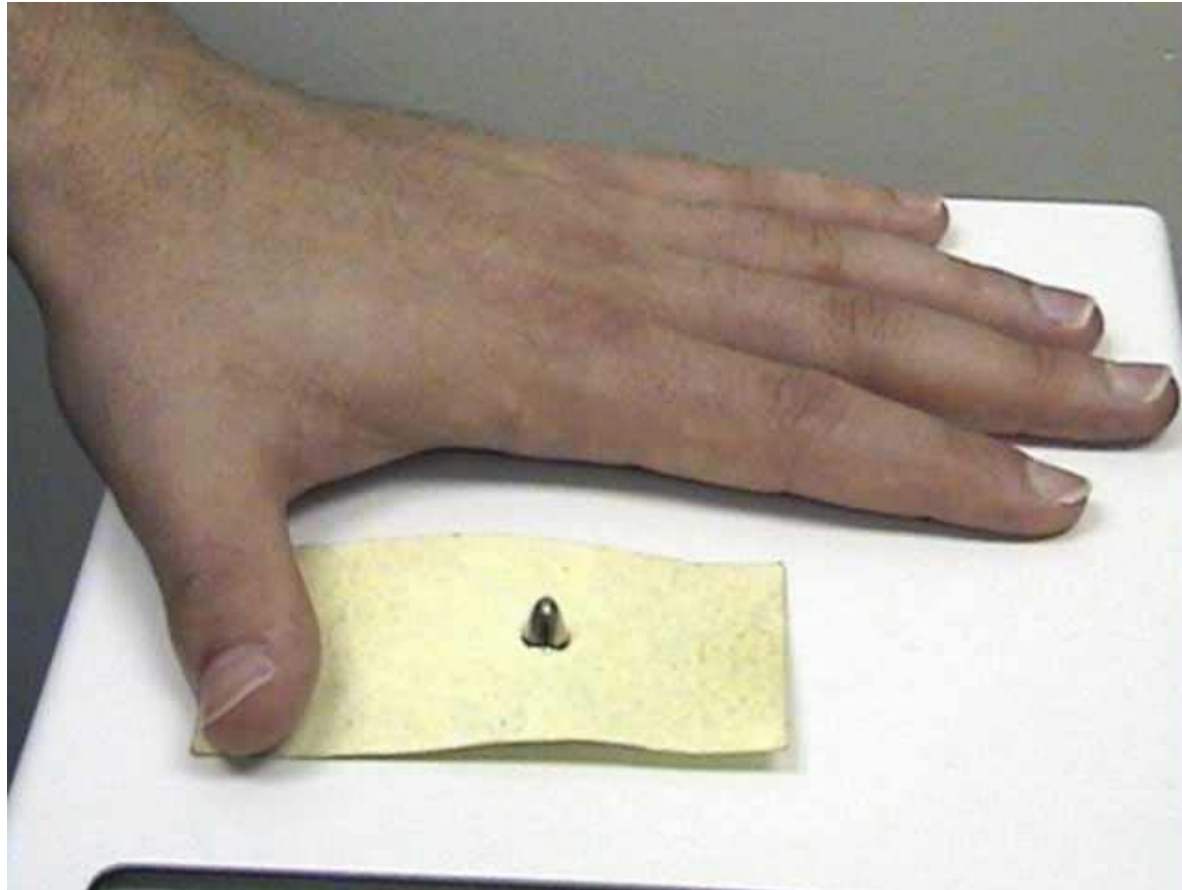
# ALP Lightcraft in Flight

The footage never shown before on public. Tssshhhhh…..



**The arrival of a laser-propelled thimble**

**Rated**: PG     **Director**: Jun Lin

**Voices**: Shane Thompson, Tim Cohen, Jun Lin

# THANK YOU